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Design and performance of district metering areas in water distribution systems

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Abstract

In large urban areas, a number of different District Metered Areas (DMAs) layouts are possible and the comparison of possible solutions is an essential part of the decision process. Therefore, when designing DMAs in a water distribution network, practitioners have firstly to evaluate the effects caused by the introduction of the districts in the system, and secondly to compare the different alternatives to determine which one is the best to adopt. In this paper a real water distribution network is considered as a case study, various possible DMAs layouts that differ in the number and the size of the districts are developed applying an automated method and an analysis of their performances is shown.

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Keywords: district metered areas; performance; non-dominated solutions.

1. Introduction

The introduction of the concept of DMAs in water distribution networks dates back to the 1980s, when it was proposed in the UK with the aim of reducing leakage. There are many examples of successful implementation of DMAs in water distribution systems (Charalambous [4], Roger [12], MacDonald and Yates [8]), nevertheless, the process of selecting district boundaries is a complex task for many reasons, such as the elaborate topology of the system, the high number of variables involved and the need to respect pressure constraints at the nodes. The complexity

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of the problem increases when dealing with large urban networks, where many feasible solutions exist. In these cases a large number of districts can be created while ensuring that the new DMAs satisfy the required criteria and when there are various possible divisions into districts that can be realised in the water distribution network. In the first place, the designer has to make sure that the introduction of DMAs does not worsen the performance of the network, thus that the minimum service levels are still satisfied. Secondly, it is crucial to analyse and compare various possible DMAs layouts, which can differ both in the number and in the chosen boundaries of the districts. This study aims firstly to investigate if and how the creation of districts affects the performance of the water distribution network, and secondly to compare a variety of feasible solutions to one another.

In order to do this, a real urban water distribution network is considered as a case study. Then, using a recently developed methodology (Ferrari et al. [6]), based on graph theory principles, a number of feasible solutions, i.e., divisions of the network into DMAs, are determined. To determine the effectiveness of the creation of DMAs, and to compare different solutions, a performance evaluation approach is used (Murray et al. [10]). A series of performance indicators (PIs), related to the parameters that describe the behavior of a water distribution network, are considered. Those indicators are: (i) the number of pipes that have to be closed to create the DMAs' boundaries, as a measure of cost, (ii) the Resilience Index (Todini [14]) as a measure of reliability, and (iii) water age, as a measure of water quality (AWWA, and EES [2]). These PIs are calculated for the original water network (with no DMAs), for the solution found following the traditional 'trial and error' approach, and for the solutions created with the graph theory based methodology (Ferrari et al. [6]). At this stage it is possible to determine the effect of the DMAs on the network original behavior and examine the differences in the performance of the various solutions.

The ultimate result of this analysis is the definition of a set of non-dominated solutions, i.e., characterised by the best value with regard to at least one of the objectives. This analysis has been carried out both in two and three dimensions, to determine the best DMAs layout with respect to its performance.

In summary, the approach followed in this study is composed of the following steps:

1. Choose a large, looped urban water distribution network (WDN), as a case study;
2. Evaluate PI (cost, resilience, water age) for the WDN;
3. Create a number of possible divisions of the WDN into DMAs, *N;*
4. Evaluate all PIs for the *N* solutions;
5. Verify that the introduction of DMAs does not worsen the performance of the WDN; and
6. Compare the *N* solution with one another (using non-domination criterion).

2. Performance of a re-designed water distribution network

First of all, a number of solutions, i.e., different DMAs layouts, has to be defined. A solution represents a possible division of the water distribution network into DMAs such that the design criteria recommended in literature are met (Farley [5], Water Industry Research Ltd [15], Morrison et al. [9]). In fact, re-designing a water distribution network in conformity to those guidelines has proven to be effective and accomplishes the objectives of the creation of DMAs.

The creation of a number of solutions has been carried out using the graph theory based methodology developed by Ferrari et al. [6]. This methodology is a fast, automatic procedure that ensures that the solutions found satisfy the most important design criteria highlighted in literature. Firstly, it allows for the definition of districts characterized by an appropriate number of customer connections, e.g., between 500 and 5000. This is important because in too large DMAs, the discrimination of bursts from night flow data is more difficult and the location of leakage takes longer. In addition, in terms of water security, the larger the district, the higher the potential exposure to pollutants, because contaminant dispersion is wider. On the other hand, small DMAs involve higher costs, because more valves and flow meters are required and also the maintenance cost increases.

In addition to creating DMAs of adequate size, this methodology ensures that the main transmission system is kept separated from the DMAs with each DMA being directly connected only to a transmission main. In other words, each DMA is independent and not connected to other DMAs. These characteristics guarantee increased water security, one of the objectives of the introduction of DMAs (Baker [3]). In fact, if a contamination accident happens, the exposure to harmful pollutants is confined and the extent of pipe that would need to be decontaminated is minimized. Consequently, water security will not be considered as a criterion to assess the performance of the solutions.

Although some authors (Morrison et al. [9]) advocate the design of DMAs that are supplied via a single main, the methodology used in this study allows the creation of multiple fed DMAs (Fig. 1). This does not adversely affect the performances of the water distribution network as multiple interconnections between a district and the transmission pipes can in some cases even be encouraged for increasing the redundancy of the system (Grayman et al. [7]).

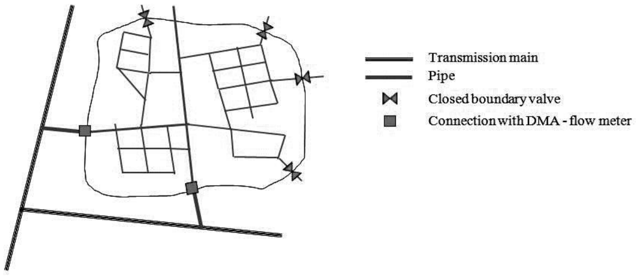

Fig. 1. Example of multi fed DMA.

The over-riding factor to take into account when redesigning a water distribution network for creating DMAs is to perform all the necessary changes without significantly affecting the quality of the service to the customers. Furthermore, the comparison of possible alternatives solutions is essential to gain a better understanding of how the hydraulics of the network is affected by different DMA layouts. Therefore, the evaluation of the performances of the redesigned network is particularly important, since it allows for the comparison between different solutions and between the solutions and the originally looped network.

Similarly to the process of designing a water distribution system, there are many factors to take into account when planning DMAs: the most important are the cost of the system implementation, the reliability of the supply, and the quality of the water delivered. As a result, evaluating the performance of a certain solution means to calculate parameters that appropriately describe the aforementioned factors. The following subsection illustrates the indicators that have been used to assess the performance of the DMAs.

2.1. Performance Indicators

In this study the following factors have been considered in the evaluation of the performance of different re-designed networks: cost, reliability, and water quality. The cost is calculated as the expenditure for the creation of DMAs' boundaries, which is the cost of the closing valves that need to be installed. Since it is proportional to the number of pipes that has to be closed in order to realize the districts, this number has been used in first approximation as an indicator of cost (Eq. 1).

$$c = n_{p,b} \tag{1}$$

where $n_{p,b}$ is the number of pipes that belongs to the DMAs' boundaries.

The reliability can be defined as the capacity of the system to supply water constantly, meeting the customer's demands, satisfying the pressure requirements and maintaining adequate flow velocities. Reliability is a crucial aspect to account for when designing a water distribution system. In fact, the satisfaction of water demands with acceptable minimum and maximum pressures is the main over-riding factor in the design process. Similarly, when the water distribution network is re-designed to introduce DMAs, the resulting system has to be sufficiently reliable.

The Resilience Index (Todini [14]) is the indicator chosen to measure reliability and its expression is given in Eq. 2. It represents the resilience as the surplus of energy available in a water distribution system: a network having a high energy surplus is highly resilient because that surplus can be dissipated internally in case of failures.

$$I_r = \frac{\sum_{i=1}^{n_n} q_i^* \left(h_i - h_i^*\right)}{\sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p} P_j / \gamma - \sum_{i=1}^{n_n} q_i^* h_i^*} \tag{2}$$

Where γ is the specific weight of water, q_i and h_i are respectively the flow and the head at each node i, n_n the number of nodes, Q_k and H_k are the discharge and the head, respectively, relevant to each reservoir k, n_k is the number of reservoirs, P_j is the power introduced into the network by the j-th pump and n_P the number of pumps. The minimum required head h^* has been fixed to 28 m (~30 psi) on each node in the network.

The indicator used to assess the quality of the water delivered is water age that is the average time required to the water to reach the users. Water age, which relates a great deal to system design and system demands, is regarded as a major factor contributing to water quality deterioration within the distribution system (AWWA and EES [2]). The longer the water takes to arrive at the demand nodes, the higher the potential for water quality degradation because chemical reactions can proceed faster and go further. Examples of water quality problems that can be caused by increased water age include disinfection byproducts (DBP) formation, decreased corrosion control effectiveness, nitrification, and microbial growth/re-growth. Since water age relates to system design, it is essential to evaluate it when re-designing the water distribution network, in order to verify that the changes made do not endanger water quality and thus human health.

To calculate the Resilience Index for each solution, a multiple-day EPANET (Rossman [13]) simulation was run, and the average values of the parameter over the whole simulation period was calculated. As for the water age, i.e., the time a parcel of water spends in the network, the software tracks the growth in water age throughout the network over time. The PI is defined as the average value over the last 24-hours of the simulation period, having total duration T (Eq. 3).

$$A = \sum_{t=T-24}^{T} \frac{A_t}{24} \quad \text{[hr]} \tag{3}$$

3. Case Study

The water distribution system chosen as a case study is an approximate model of a real world system, which is frequently used as a test bed for various modelling exercises including the Battle of the Water Sensor Networks competition (Ostfeld, et al [11]). The network, represented in Fig. 2, serves roughly around 150,000 people and represents a good example of relatively large urban water distribution system. It comprises 12,522 nodes, 14,820 pipes, five valves (four flow control valves and one pressure reducing valve), three reservoirs, two tanks and four pumps. Some alterations have been made to the geographic representation and to the names of the components in order to protect the identity of the system. These alterations are related only to the appearance and do not have any influence on the connectivity and the hydraulic behavior of the network.

Grayman et al. [7] were the first to report how this water distribution network was divided into DMAs with the main purpose of reducing the impacts deriving from contamination accidents. The redesign of the network was done following a trial and error approach, i.e., performing modifications manually while taking into account the recommendations about district's size and independency of adjacent DMAs (Baker [3]). The initial aim of establishing a single connection between a district and the transmission main lead often to infeasibility, i.e., negative pressures in the network: hence, it was further modified to achieve at least two connections in order to ensure a sufficient redundancy within the system. The performance of the network divided into DMAs with this approach will be considered in the analysis, along with those of the solutions found following the graph theory based methodology (Ferrari et al. [6]).

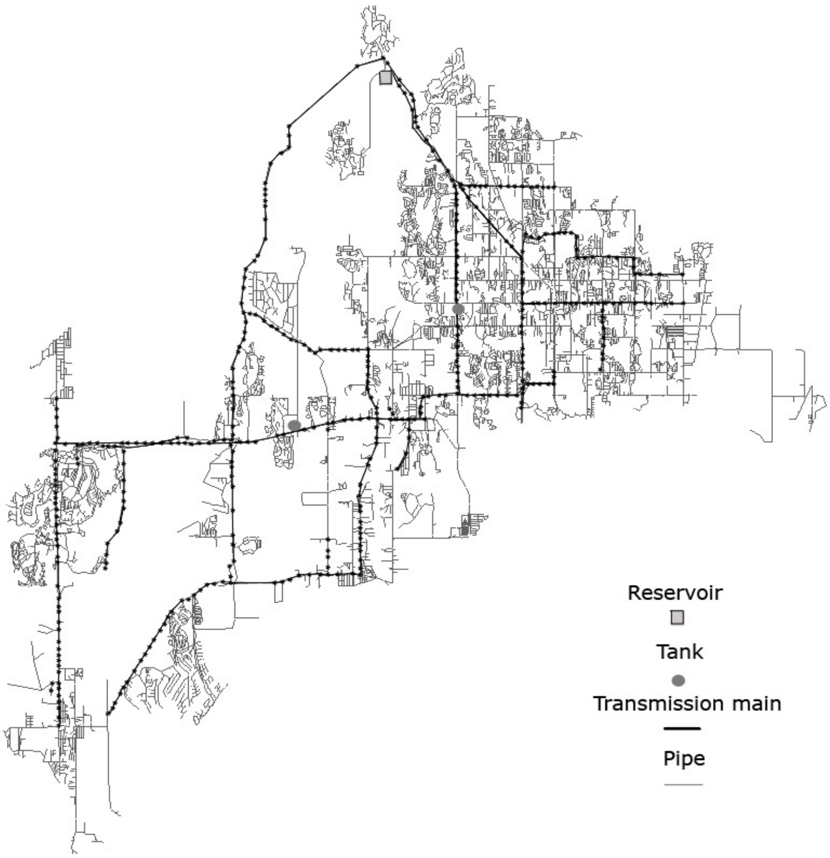

Fig. 2. The water distribution network used as a case study.

4. Results

A number of feasible solutions (N = 116), characterized by having between 32 and 43 DMAs, have been created using the graph-theory based methodology mentioned in section 2. An EPANET simulation has been run for each solution and the performance indicators for the N possible divisions of the water distribution network into districts have been evaluated. In the first place it is important to check whether the creation of DMAs affects the quality of the service to the users, i.e., if a deterioration of the value of the PIs is observed in the networks with DMAs respect to the network without DMAs (looped).

Table 1. Performance comparison between the looped network and the DMAs.

Performance Indicator	Looped	DMAs
Water Age (hours)	30.71	31.04 – 31.62
Resilience index (average)	0.84	0.81 – 0.82
Resilience index (min)	0.64	0.61 – 0.63
Resilience index (max)	0.93	0.93 -0.94

Results shown in Table 1 indicate that the introduction of DMAs causes a decrease of the performances, both in water quality and in resilience. Specifically, an increase in water age of 20 to 55 minutes is observed together with a reduction between 0.03 and 0.16 for the average Resilience Index. However, this decline is not considered significant, as it is compensated by the benefits that the DMAs bring in terms of improved management of the system, reduced water security risks and leakage control.

4.1. Performance Indicators

Graphs in Fig. 3 illustrate how the PI values vary with the number of DMAs. They outline how the PIs depend both on the number of DMAs and on the boundaries of the DMAs, i.e., on which pipes will be closed.

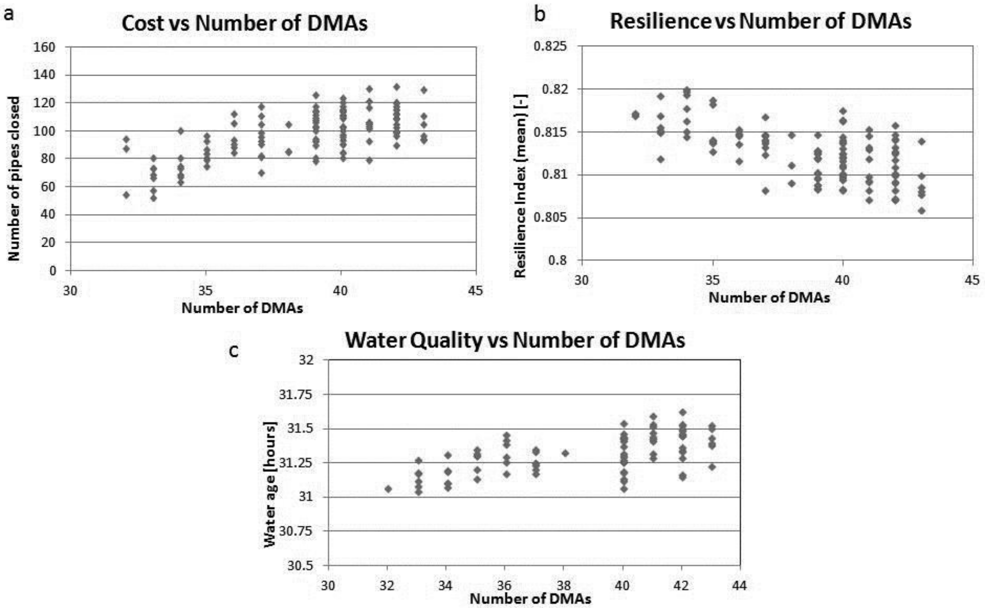

Fig. 3. (a) Cost vs Number of DMAs; (b) Resilience vs Number of DMAs; (c) Water Quality vs Number of DMAs.

The data shows that an increase in the number of DMAs in the network is generally associated with decay in the performances. The results also outline that the variations in the cost are quite significant, ranging from 53 to 132 closed pipes to create the districts, while the variations in the values of the other two indicators are small. For example, Resilience Index fluctuates between 0.81 and 0.82, and water age between 31.04 and 31.62 hours. Furthermore, a high variance can be noticed among solutions having the same number of DMAs, but different boundaries. Thus, for any indicator, it is possible to identify one best solution corresponding to a fixed number of DMAs, which yet might not be the best one with respect to the other indicators. As a matter of fact, like in every multi-objective problem, there is not only one optimal solution, but a set of non-dominated solutions.

4.2. Comparison of the solutions

The performance indicators have been compared in pairs at first and the solutions lying on these 2D non-dominated fronts have been determined (represented by the black line in the figures below). The value of the performances corresponding to the solution found following the traditional ‘trial and error’ approach (Grayman [7]) is represented on the graphs with the symbol ‘x’. Fig. 4 reveals that an increment in the value of Resilience Index is associated to a reduction in the water age, which means that more resilient solutions are also characterized by a better water quality. Fig. 5 and Fig. 6 also show that the cost rises for solutions having a lower value of Index and higher water age. This is due to the fact that the cost is proportional to the number of closed valves, and the higher the number of pipes to be closed, the less resilient is the system, because there are fewer paths available for the flow in the network. For the same reason, the water takes longer to reach demand nodes, resulting in a higher value of the water age.

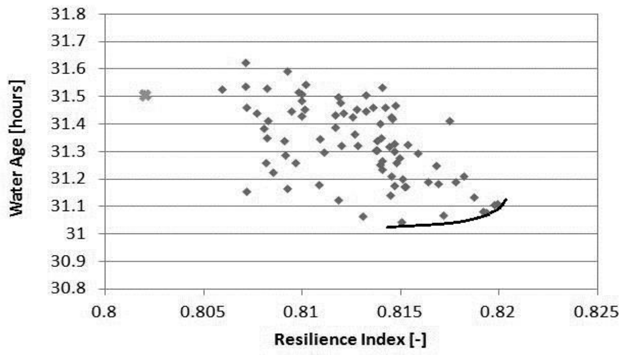

Fig. 4. Water quality vs Resilience.

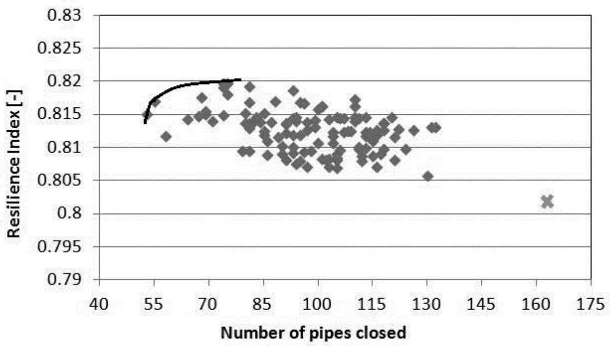

Fig. 5. Resilience vs cost.

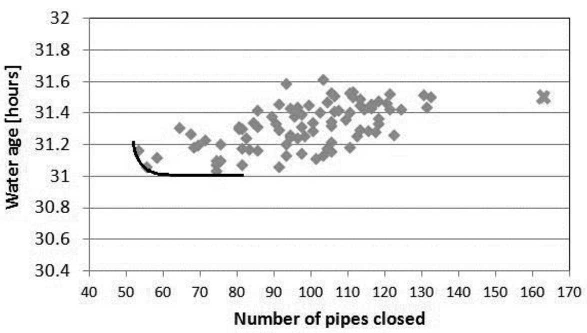

Fig. 6. Water quality vs Cost.

5. Conclusion

In this paper the performance of a number of different feasible divisions of a given water distribution network into DMAs have been analyzed. The first outcome is that the design of DMAs, if carried out with a methodology that takes into account the design criteria recommended in literature, does not worsen the quality of the service to the customers neither in terms of reliability nor in terms of quality of the water delivered. The results show only a minor decline in the performances, which is irrelevant compared to the benefits produced by the DMAs in terms of reduction of leakage, improved water security, and better control and management of the network.

Secondly, three different indicators that measure cost, reliability and water quality, which relate to the objectives that are usually taken into account when re-designing a water distribution network, have been considered. Their value has been evaluated for a number of possible solutions and a performance analysis has been carried out: as a result the best solutions with respect to the three aforementioned objectives have been identified. Further developments of this study would include the evaluation of additional objectives such as the ability of the solutions to meet fire flows and their performance in terms of reduction of leakage.

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